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CERTIFICATION

I, the below named translator, hereby declare that: my name and post office address are as stated below; that I am knowledgeable in the English and German languages, and that I believe that the attached text is a true and complete translation of PCT/EP2005/050148, filed with the European Patent Office on January 14, 2005.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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1 CIRCUIT CONFIGURATION AND METHOD FOR GENERATING A CONTROL
2 SIGNAL FOR AN ENGINE CONTROL UNIT DESIGNED TO CONTROL FUEL
3 INJECTORS
4

5 The present invention relates to a circuit configuration and
6 also a method for generating a control signal for an engine
7 control unit designed to control a fuel injector of an
8 internal combustion engine.

9
10 In particular the exhaust gas standards for engines which
11 have become more stringent in recent times have brought about
12 the development of fuel injectors with fast and
13 instantaneously responding final control elements or
14 actuators in the motor vehicle industry. With regard to the
15 practical realization of such types of final control
16 elements, piezoelectric elements particularly have proved to
17 be advantageous. Such types of piezo elements are usually
18 made up of a stack of piezo ceramic disks which are operated
19 by way of an electrical parallel circuit in order to be able
20 to achieve the electrical field strengths required for an
21 adequate stroke.

22
23 The use of piezoelectric ceramic for operation of fuel
24 injection valves of an internal combustion engine places
25 considerable demands on the electronics for charging and
26 discharging the piezo ceramic. In this situation,
27 comparatively high voltages (typically 100V or more) and
28 briefly comparatively high currents for charging and
29 discharging (typically more than 10A) need to be made
30 available. In order to optimize the engine characteristics
31 (for example exhaust gas values, performance, consumption
32 etc.), these charging and discharging operations should take
33 place in fractions of milliseconds with simultaneously

1 extensive control over current and voltage.

2
3 With regard to the engine control units previously used,
4 including a final stage for the operation of one or more
5 piezo fuel injectors, the charging and discharging current
6 forms are more or less predefined by the particular operating
7 principle of the circuit or can only be changed within
8 relatively narrow limits.

9
10 Thus, for example, a final stage for controlling piezo fuel
11 injectors is known from DE 199 44 733 A1. This known final
12 stage is based on a bidirectionally operating reverse
13 converter and enables a metering of energy portions when
14 charging and discharging the piezoelectric ceramic of the
15 fuel injectors, such that on principle the charging and
16 discharging current forms can be realized in adapted form as
17 average current waveforms. The desired current waveforms when
18 charging and discharging the piezo elements are defined here
19 by means of a control circuit, not described in detail in
20 this publication, which for this purpose measures the actual
21 charging and discharging currents flowing (with reference to
22 voltage drops at current shunts) and controls the charging
23 and discharging operations based on these measurement values.
24 In order to charge a piezo element a charging switch is
25 controlled with a predefined frequency and predefined pulse
26 duty ratio in pulsed operation with a predefined number of
27 pulse-width modulated signals, whereas in order to discharge
28 a piezo element a discharging switch is controlled in pulse
29 form to be conducting and non-conducting.

30
31 If an engine control unit for controlling at least one fuel
32 injector, as are already known in numerous embodiments, is
33 intended to control the fuel injectors in a regulated manner,

1 then a control signal is required for this regulation which
2 represents the "reference value" for a desired timing
3 characteristic with regard to controlling an injector, for
4 example charging or discharging a piezo injector.
5 Particularly as a result of the control operations which
6 occur relatively rapidly, as already mentioned above,
7 extremely simple regulation facilities or reference value
8 control signals have been employed for those engine control
9 units used hitherto. The control waveforms which then result,
10 for example charging and discharging current forms, are not
11 optimal in this respect with regard to piezo injectors.

12
13 The object of the present invention is therefore to set down
14 a way of generating a control signal for an engine control
15 unit for controlling at least one fuel injector of an
16 internal combustion engine, with which improved control
17 signal waveforms can be realized with regard to injector
18 control.

19
20 This object is achieved by a circuit configuration according
21 to Claim 1 or a method according to Claim 10. Advantageous
22 developments of the invention are set down in the dependent
23 claims.

24
25 The circuit configuration according to the invention for
26 generating a control signal for an engine control unit for
27 controlling at least one fuel injector of an internal
28 combustion engine comprises:

- 29
30 - a counter device, to which a predefined clock signal
31 can be supplied, for providing a time-dependent
32 digital counter signal, based on the counting of the
33 clock signal, whereby the clock signal is predefined

1 with a frequency which is selectable depending on the
2 modification signal,

3
4 - a memory unit, to which the digital counter signal can
5 be supplied, for storing a series of digital control
6 signal values and for the successive issue of
7 individual control signal values from the series of
8 control signal values, in accordance with the counter
9 signal, and

10
11 - a digital-to-analog converter unit for converting the
12 issued digital control signal values into the analog
13 control signal for the engine control unit, whereby
14 the conversion of the digital control signal values
15 into the analog control signal is implemented by
16 taking the modification signal into account as an
17 amplitude scaling signal.

18
19
20 It is thus possible in a simple manner to generate a control
21 signal adapted to the particular application situation as a
22 predefined reference value for the regulated control of a
23 fuel injector with practically any desired control waveform
24 (for example charging and discharging current form).
25 Essential in this situation is the storage of a digital
26 series of control signal values, from which individual
27 control signal values are issued in succession during
28 operation of the circuit configuration and converted into the
29 analog control signal. In particular it is thus not
30 necessary, as previously, to accept compromises in respect of
31 the charging and discharging current forms with regard to
32 piezo injectors. Rather, these forms can be optimally adapted
33 to the respective requirements.

1
2 As a result of the free definability of the waveforms of
3 charging and discharging currents for piezo injectors and/or
4 the voltages present at such piezo injectors, it is thus
5 possible to comply with the requirements both in respect of a
6 variable stroke size for the piezo actuators and also of the
7 injection duration whilst simultaneously minimizing the
8 acoustic emission. The fuel injectors or the control thereof
9 can be optimized in respect of the desired valve opening and
10 valve closing speeds, the masses moved during opening and
11 closing and the (as a rule non-linear) characteristics of the
12 conversion of an actuator stroke into the valve opening or
13 valve closing (for example hydraulic conversion in the case
14 of a piezo servo valve). In laboratory trials, for example,
15 ideal charging and discharging current curves for piezo servo
16 valves have been determined which run relatively "gently" and
17 for example similar to the " \sin^2 " function. By using the
18 solution according to the invention, appropriate control
19 signals for predefining reference values can be generated in
20 a simple manner with regard to regulated injector control.

21
22 In a preferred embodiment, provision is made whereby the
23 clock signal is predefined with a selectable frequency. The
24 waveform of the corresponding control signal can thus be
25 scaled in time for one and the same stored series of control
26 signal values. Setting a lower frequency then results, for
27 example, in the control signal values being read out at a
28 lower clock frequency (more slowly) from the memory unit.
29 This frequency setting can be used in this situation both for
30 adapting the control signal waveform to the properties of a
31 particular one of a plurality of injectors and also for
32 adapting this control signal waveform to actual operating
33 conditions for the internal combustion engine or injection

1 system in question. Such types of adjustments in this
2 situation can be made in real time without any difficulty.

3
4 There are numerous possible ways of setting the clock
5 frequency. For example, a voltage controlled oscillator (VCO)
6 to which a time scaling signal is applied can be used in
7 order to provide the clock signal with the selected
8 frequency. In another embodiment, an oscillator with a fixed
9 oscillation frequency and a divider, connected downstream of
10 the oscillator, is used here whose division ratio is
11 determined by a time scaling signal input to the divider.

12
13 By preference, a series of at least 30, in particular at
14 least 50 control signal values, is provided as the series of
15 control signal values stored in the memory unit. A
16 sufficiently precise definition of the control signal
17 waveform results in practice for the majority of cases from
18 using such a number.

19
20 With regard to the optimized control curves determined in
21 laboratory trials for the current or for charging in the case
22 of piezo injectors it is advantageous if the series of
23 control signal values stored in the memory unit approaches a
24 continuous function. For predefining the reference value for
25 the charging or discharging current waveform in the case of a
26 piezo injector, a series which approaches a continuous, in
27 particular a continuously differentiable, "bell function" has
28 for example proved to be particularly advantageous. In one
29 embodiment, the series is composed of a monotonically
30 increasing series section and a monotonically decreasing
31 series section, which together approach the bell curve.

32
33 With regard to the precision of the definition of the control

1 signal waveform it is advantageous in the majority of
2 applications if the digital control signal values are
3 provided with a resolution of at least 8 bits.

4
5 Although it is conceivable that the stored series of control
6 signal values can be changed, for example by using a
7 read/write memory and operational updating of the stored
8 data, then the setup or operation of the circuit
9 configuration is considerably simplified if either one or
10 more selectable series of control signal values is
11 permanently predefined by the stored data. In one embodiment,
12 provision is therefore made whereby the memory unit takes the
13 form of a read-only memory.

14
15 It is also possible on the basis of a series of control
16 signal values which is permanently predefined during
17 operation to provide the control signal waveform in variable
18 or adapted form. One possible way of doing this is the
19 aforementioned setting of the frequency of the clock signal,
20 which causes a temporal scaling of the control signal
21 waveform.

22
23 As an alternative or in addition, it is for example possible
24 for modification of the control signal waveform to take into
25 consideration an amplitude scaling signal value when
26 providing the conversion of the digital control signal values
27 into the analog control signal. Such an amplitude scaling
28 signal value can for example be entered at a reference input
29 of a digital-to-analog converter which is provided for this
30 purpose, such that the output signal from the converter has
31 its amplitude scaled in accordance with the entered amplitude
32 scaling signal value.

1 In a preferred embodiment, provision is made whereby a time
2 scaling signal provided for setting the clock signal
3 frequency and an amplitude scaling signal provided for
4 setting the amplitude of the control signal are identical or
5 are derived from one another or from a common scaling signal.
6 It is thus possible, for example, in a particularly simple
7 manner to furnish different charging final values
8 (corresponding to different strokes of a piezo injector) when
9 the charging time or discharging time is also scaled.

10
11 Finally, the control signal waveform can also be modified,
12 for example, in that the counter device or a digital
13 conversion device connected downstream of the counter device
14 is provided in such a way that a re-coding of the counter
15 signal takes place for this modification before it is used as
16 an address signal.

17
18 The adaptation of the control signal waveform can for example
19 be provided with regard to manufacturing-dependent tolerances
20 affecting the controlled fuel injectors. It can be the case,
21 for example, that piezo elements incorporated in different
22 fuel injectors require different charging final values during
23 the injector opening process in order to open the injector
24 valve to its full extent. Such types of tolerances can for
25 example be compensated for by providing an appropriately
26 adapted scaling signal. Sensor signals, supplied by so-called
27 position or limit stop sensors of the injector arrangement,
28 which are often available in any case can for example
29 advantageously be used for such an adaptation to the
30 characteristics of a fuel injector or of the final control
31 element used therein. Such types of sensors for the realtime
32 recording of the characteristics and/or the actual course of
33 motion in fuel injectors are adequately known and do not

1 therefore require any detailed description.

2
3 Furthermore, for example, the following operating parameters
4 for the internal combustion engine or injection system in
5 question can be evaluated and used for adapting the control
6 signal waveform: pump prepressure (for example rail
7 pressure), temperature (in particular temperature of the
8 injector and/or of the fuel), rotational speed and load of
9 the internal combustion engine etc.

10
11 The invention will be described in detail in the following on
12 the basis of several embodiments with reference to the
13 attached drawings. In the drawings:

14
15 Figure 1 illustrates a comparison of two waveforms for the
16 control signal (voltage) for a piezo injector,

17
18 Figure 2 illustrates a comparison of two further waveforms
19 for the control signal for a piezo injector,

20
21 Figure 3 illustrates a comparison of two further waveforms
22 for the control signal for a piezo injector,

23
24 Figure 4 shows a block diagram of a circuit configuration
25 for generating different control signal waveforms
26 for an engine control unit for controlling one or
27 more fuel injectors,

28
29 Figure 5 shows a block diagram of a circuit configuration
30 for generating different control signal waveforms
31 for an engine control unit for controlling one or
32 more fuel injectors in accordance with a further
33 embodiment,

Figure 6 shows a block diagram of a circuit configuration for generating different control signal waveforms for an engine control unit for controlling one or more fuel injectors in accordance with a further embodiment, and

Figure 7 shows a block diagram of an engine control unit in which a circuit configuration according to Figure 4 is used for controlling piezo fuel injectors.

With regard to the waveforms illustrated in Figures 1 to 3, these are control voltages as they are applied to the piezo element by an engine control unit of a motor vehicle for opening a fuel injection valve operated by means of a piezo element.

As a result of the predefined electrical capacitance of the piezo element, the waveforms illustrated also correspond to the characteristic of the charge quantity stored into the piezo element.

Figure 1 shows two voltage curves or waveforms U1, U2 for the piezo voltage U_p plotted against the time t . The two waveforms U1 and U2 have different piezo voltage final values Uend1 and Uend2, whereby in the example illustrated the final voltage Uend2 of the piezo voltage curve U2 is half of the voltage final value Uend1 of the piezo voltage curve U1.

The two piezo voltage curves U1, U2 have qualitatively the same shape which namely results for a piezo charging current curve with precisely one maximum similar to the \sin^2 function, whereby the curves U1, U2 in the time range are scaled with

1 the voltage final value reached at the end. In the example
2 illustrated this means that the charging time duration
3 denoted by t_3' for the curve U2 is half the charging time
4 duration t_3 for the curve U1. Accordingly, the times t_1' and
5 t_2' likewise entered in the figure, at which the piezo
6 voltage U_p for the curve U2 reaches 20% and 75% respectively
7 of the voltage end value U_{end2} , likewise amount to half of
8 the corresponding times t_1 and t_2 for the curve U1. From this
9 simultaneous scaling of the voltage or charging final value
10 and the charging time results a maximum charging current for
11 the piezo element, equal for both curves U1 and U2, which is
12 expressed in the figure by an equal maximum gradient of the
13 curves U1 and U2.

14
15 With regard to the waveforms U1 and U2 these are to a certain
16 extent optimized curves of a qualitatively predefined shape,
17 which on account of the scalability can be employed
18 advantageously for the control of fuel injectors having
19 different control characteristics or for the control of fuel
20 injectors having a variable actuation stroke.

21
22 Figures 2 and 3 are illustrations corresponding to Figure 1
23 for other voltage curves U1 and U2.

24
25 As opposed to Figure 1, Figure 2 shows an additional scaling
26 (extension) in the time range for the voltage curve U2, as a
27 result of which the charging current needed with this curve
28 is reduced and a shift of the acoustic spectrum to lower
29 frequencies is advantageously achieved.

30
31 Figure 3 shows a further possible option for shaping two
32 voltage curves U1 and U2 with different voltage final values.
33 In this situation the piezo voltages U_p take an identical

1 course up to the point in time $t_1=t_1'$ and deviate from one
2 another until reaching the respective voltage final values
3 U_{end1} , U_{end2} .

4
5 Circuit configurations for generating a control voltage U_s
6 which is suitable as a "reference value" for charging and
7 discharging currents for realization of the piezo voltage
8 curves illustrated in Figures 1 to 3 are described in the
9 following with reference to Figures 4 to 6.

10
11 Figure 4 shows a circuit configuration, denoted overall by
12 10, for generating a control signal U_s for an engine control
13 unit for the control of fuel injectors, whereby the control
14 signal U_s generated is suitable within the framework of a
15 regulated piezo control facility for predefining the piezo
16 current reference value for the piezo voltage curves U_1 , U_2
17 shown in Figures 1 to 3, as is described in the following.

18
19 The circuit configuration 10 includes a counter 12, supplied
20 with a clock signal f_c , which - triggered by a start signal
21 which is not shown from an engine control electronics unit -
22 counts the clock signal f_c (from 1 to N) and provides a time-
23 dependent digital counter signal X as the result of this
24 counting. In the simplest case the signal X represents the
25 number of clock signal periods executed up to the current
26 point in time.

27
28 This digital counter signal X is entered into a memory 14 as
29 an address input signal. In this memory 14, a series Y of
30 digital control signal values Y_1 , Y_2 ... Y_N with a resolution
31 of K bits which were stored in advance are output in
32 succession to a digital-to-analog converter 16 depending on
33 the counter signal X entered for addressing.

1
2 The digital-to-analog converter 16 converts the digital
3 control signal values Y_1 , Y_2 ... into the analog control
4 signal U_s which is used in an engine control unit not shown
5 in this figure as the predefined reference value for the
6 piezo current to be output and consequently for the resulting
7 (as the integral of the current) charge (and proportional to
8 this, the piezo voltage U_p).

9
10 The data stored in the memory 14, in this case a list or
11 table with N control signal values each with K bits
12 resolution (here: $N=100$, $K=10$) represents the desired, time-
13 related reference value curve, determined in advance and
14 optimized, for an injector control current intended for
15 injector valve opening. For the valve closing operation, the
16 same curve (inverted) or a different curve specially stored
17 for this purpose in the memory 14 can be provided.

18
19 The concrete shape of the output signal U_s here is also
20 determined by two parameters. The first of these is the
21 frequency of a permanently predefined clock signal f_0 which
22 is generated by a clock generator not shown in Figure 4 and
23 input by way of a divider 18 to the counter 12 as a frequency
24 divided clock signal f_c . The second of these is a digital
25 scaling signal S (output by a microcontroller for example)
26 which on the one hand is input directly to the divider 18 and
27 whose division ratio is determined and on the other hand is
28 input by way of a digital-to-analog converter 20 in analog
29 form to a reference input Ref of the digital-to-analog
30 converter 16. The scaling signal S thus serves on the one
31 hand as a time scaling signal which on the basis of the
32 division ratio dependent thereon of the divider 18 determines
33 the clock for reading data from the memory 14 and thus the

1 charging time period, and on the other hand as an amplitude
2 scaling signal which is taken into consideration as a
3 multiplicative parameter during the output-side conversion by
4 the digital-to-analog converter 16.

5
6 If the circuit configuration according to Figure 4 is
7 operated with a permanently predefined basic frequency f_0 but
8 a variable scaling signal S , then the voltage curves U_1 and
9 U_2 shown in Figure 1 can be realized in a simple manner
10 through appropriate setting of the scaling signal S (for
11 example by the aforementioned microcontroller). The
12 transition from the voltage curve U_1 to the voltage curve U_2
13 occurs for example as a result of halving the scaling value
14 represented by the signal S .

15
16 The variation of the voltage curve illustrated in Figure 2
17 can also be realized in a simple manner with the circuit
18 configuration according to Figure 4. In contrast to the
19 operation with a fixed basic frequency f_0 , for a transition
20 from the voltage curve U_1 to the voltage curve U_2 in Figure 2
21 only an additional reduction in the frequency of the signal
22 f_0 input to the divider 18 needs to be provided here (in
23 order to achieve the additional extension or slowing of the
24 piezo voltage rise for the voltage curve U_2). As an
25 alternative or in addition, for the curve scaling according
26 to Figure 2 (deviating from the embodiment illustrated in
27 Figure 4) the time scaling signal fed to the divider 18 could
28 also be chosen to be not equal to the amplitude scaling
29 signal which is input to the converter 16 as a reference.

30
31 Finally, the variation of the voltage curve illustrated in
32 Figure 3 can also be realized with the circuit configuration
33 according to Figure 4, depending on the desired voltage

1 curve, by not running through (outputting) the complete
2 stored series of control signal values Y1, Y2 ... YN but by
3 skipping a middle range from this stored series (in Figure 3
4 the range between t1 and t2).

5
6 For this purpose the counter 12 can be configured as
7 controllable or programmable in such a manner that the output
8 of control values for a middle range of addresses
9 corresponding to a preselected control value amplitude is
10 suppressed. The latter is done for example by combining the
11 counter with a control logic which provides a modifiable code
12 conversion of the signal X before it is output to the memory.

13
14 The circuit configuration 10 for realizing one of more of the
15 control methods described with reference to Figures 1 to 3
16 (on the basis of an optimized control curve) can easily be
17 implemented in hardwired logic, in other words particularly
18 also without using a microcontroller, such that an extremely
19 high speed of execution in the microsecond range can be
20 attained. In this respect it is advantageous if when choosing
21 the values N, K, S binary multiples are used which can then
22 for example be set extremely rapidly by means of an
23 appropriate bit shift operation.

24
25 Alternatively, the method can however also be realized with a
26 microcontroller or a digital signal processor (DSP) if the
27 realtime requirements are not excessively high. In this case,
28 control circuit sections provided in the appropriate
29 circumstances, for example for the piezo control voltage (or
30 piezo charging), are easier to realize and reduce the need
31 for analog circuitry, which makes the overall arrangement
32 more cost-effective.

Figures 5 and 6 show two further modifications of the circuit configuration according to Figure 4, whereby analog circuit components are denoted in these figures by the same reference numbers but are incremented by 100 (Figure 5) or 200 (Figure 6) in each case in order to differentiate the embodiments.

With regard to the modification according to Figure 5, an analog scaling signal S is provided which is input in this form directly to the reference input Ref of the digital-to-analog converter 116 and by way of an analog-to-digital converter 122 in digital Form to the divider 118.

With regard to the modification shown in Figure 6, in order to provide the clock signal fc a voltage controlled oscillator (VCO) 224 is used to which the scaling signal S is applied for setting the frequency. This signal S is also fed to an analog multiplier element 216-2 which is connected downstream of a digital-to-analog converter 216-1 and together with the latter forms the digital-to-analog converter unit 216.

In a schematic block diagram, Figure 7 illustrates the use of the circuit configuration 10 described above for the operation of a final stage 1 in an engine control unit ECU for the regulated charging and discharging of piezo elements in fuel injectors.

The engine control unit ECU includes the circuit configuration 10, which receives as its input on the one hand the basic clock signal f0 from an oscillator 4 and on the other hand the scaling signal S from a microcontroller 3. In the manner already described above, the circuit configuration 10 thereby generates an analog control signal Us which is fed

1 to a control unit 2 of the engine control unit ECU as a
2 predefined reference value.

3
4 Amongst other things, four selection signals select1 to
5 select4 are generated by the control unit 2 and fed to the
6 final stage 1. These signals select1 to select4 are initially
7 used to select one of four fuel injectors immediately prior
8 to a fuel injection.

9
10 The piezo control voltage (one of the voltages Up1 to Up4) is
11 subsequently fed to the piezo element of the selected fuel
12 injector. This process is initiated by the output of a PWM-
13 modulated charging signal up from the control unit 2 to the
14 final stage 1. In the final stage 1 the signal up is for
15 example fed to the gate of a power MOSFET in order to switch
16 the latter on in clocked mode for charging the corresponding
17 piezo element. Control of the discharging of the piezo
18 element is effected in analogous fashion through the
19 generation of a corresponding PWM-modulated discharging
20 signal down which is used for example to control a power
21 MOSFET provided for discharging purposes.

22
23 The PWM control, in particular the pulse duty ratio of the
24 charging and discharging signals up and down is based here on
25 a control process by means of which an actual value (here:
26 charging/discharging current Ip, alternatively for example:
27 piezo voltage Up), which is representative of the control
28 status of the injector currently being controlled, is
29 compared in the control unit 2 with a corresponding
30 predefined reference value (here: control signal Us provided
31 by the circuit configuration 10), and the modulation of the
32 signals up and down is set for bringing the actual value
33 (piezo current actually flowing) into line with the reference

1 value U_s .

2

3 In order to take engine operating parameters into
4 consideration during this controlled operation of the fuel
5 injectors, parameters such as for example the pressure p in a
6 fuel pressure reservoir, the temperature T of the fuel in the
7 area of the injectors etc. are here fed as sensor signals to
8 the control unit 2 and, involving the microcontroller 3 if
9 the occasion arises, evaluated.

10

11 Although in the case of the embodiments described above the
12 control signal U_s represents the predefined value for a
13 current to be output to a piezo element, this is however not
14 restrictive for the invention. Rather, the control signal
15 generated in accordance with the invention can also represent
16 any other value representative of the control status or the
17 control waveform for a fuel injector, in particular the
18 charging status or charging/discharging voltage of a
19 piezoelectric final control element.

20

21

22